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A systematic review of the green and sustainable chemistry education research literature in mainland China

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ABSTRACT

This paper describes state-of-the-art green and sustainable chemistry education (GSCE) research in mainland China based on a systematic review of the literature. The current situation in secondary and tertiary education is explored and compared. Our analysis found that research in GSCE for secondary education basically focuses on the introduction of teaching strategies and on 'greening' required chemistry experiments. Socio-scientific issues-based teaching is initially concerning. Secondary school students' and teachers' awareness of and behaviors surrounding green chemistry are generally weak; related teaching examples or models remain a rare occurrence. In tertiary education, multiple teaching methods are reported and changes in practical work are more elaborated. Overall, GSCE research literature in mainland China is in its preliminary stage, while the currently used chemistry curriculum standards highlight the importance of GSCE at the high school level, which brings a new chance for developing GSCE in Chinese chemistry education. Some suggestions for GSCE in mainland China are derived from the results.

1. Introduction

Environmental pollution, the deterioration of ecosystems, climate change, limited natural resources, and suggested changes in energy use are a few of the unprecedented set of challenges the global community faces today, in line with the development of modern industrial civilizations. These problems are accelerating as human pressure on the earth continues to increase (United Nations Environment Program [UNEP], 2012; Zhu, 1997). The societal and economic development of more and more countries is concerned with sustainable development. The Brundtland Report by the United Nations (UN, 1987, para. 1) first defined it: "Sustainable development is development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs." Although the definition of sustainable development or sustainability has been continuously refined (Dobson, 1996; Sjöström et al., 2016), its core idea has stayed the same. It relates to keeping living conditions on earth sustainable and attempts to raise human beings' awareness of a sustainably working balance of ecological, economic, and societal development (Burmeister et al., 2012).

Education for Sustainable Development (ESD) as a worldwide political goal was first coined in Agenda 21 by the United Nations Conference on Environment and Development (UNCED, 1992). It suggested that everyone be empowered to make informed decisions. This included environmental integrity, economic viability, peace, and justice in society for both present and future generations, with an eye to respecting the many facets of diversity. To build a more sustainable world, the United Nations Educational, Scientific and Cultural Organization (UNESCO, 2002) declared the decade of 2005–2014 as the Decade of Education for Sustainable Development (DESD). DESD was initiated to promote life-long learning about sustainability occurring in a wide range of settings in formal, non-formal, or informal contexts and is an integral part of quality education (UNESCO, 2005, 2014, 2016). This view was recently forwarded into *the* Agenda 2030 where the United Nations (UN) suggested: "By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles …" (see Goal 4.7: UN, 2015, p. 17).

The key role ESD plays in addressing sustainable development is to pave the way for a more sustainable future (Pauw et al., 2015). ESD is as an enabler for sustainable development. It simultaneously boosts educational innovation and involves all levels and areas of education in general (UNESCO, 2012, 2014) and in chemistry education in particular (Burmeister et al., 2012). Chemistry education plays an important role

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in ESD because chemistry is closely related to modern industry, which seeks more sustainable products and production processes in every part of people's lives (Hofstein and Kesner, 2006). One answer to the many challenges faced by sustainable development is the concept of green and sustainable chemistry. This idea addresses a changed philosophy of how to apply chemistry and how to develop more sustainable processes and products (UNEP, 2019). Since the application of chemistry is one of the suggestions for change, we must also look at the question of how chemistry is taught and learned at the secondary and tertiary educational levels (UNEP, 2019). Since the ideas of green and sustainable chemistry are quite new, a logical first question arises: What does the state-of-the-art in the chemistry education literature in mainland China concerning green and sustainable chemistry education actually look like as it can be derived from published research and practice? This paper represents an analytical review of the current literature, and intends to identify the present situation and trends in green and sustainable chemistry education as it can be identified from the literature. It goes beyond this analysis to claim mapping each detail of research and common practices in mainland China concerning green and sustainable chemistry education, and it only can map a picture and identify trends from published research (under inclusion of published practical contributions).

1.1. Green and sustainable Chemistry Education

The terms green chemistry and sustainable chemistry were introduced into chemistry in the 1990s. Since then these terms and their associated concepts have been under constant debate and with continual development (Centi and Perathoner, 2009; UNEP, 2019). Although the general ideas behind both terms seem to be quite clear, there are varying interpretations in detail (Zuin et al., 2021). This section seeks to clarify the terms as being used in this review. It does not claim to provide the correct interpretation, but it does provide one potential interpretation, which is used further in this paper.

1.1.1. Green chemistry

In the 1990s, a new idea for changing chemistry practices emerged in the USA, which was proposed by Paul Anastas and John Warner: "Green chemistry" (Anastas and Warner, 1998). The term "green chemistry" has spread outwards from the United States and is still the most-used term in English-speaking countries for chemistry viewed in terms of sustainability. The main idea of green chemistry is incorporated in 12 principles aimed to reduce or eliminate risks, resource consumption and the generation of hazardous substances during the design, manufacture, and application of chemical products (Anastas and Warner, 1998). These principles were suggested to serve as the core for future chemistry by integrating sustainability into chemistry and its innovations (Manley et al., 2008). Green chemistry searches for innovative scientific solutions for industrial production and real-world environmental problems (Karpudewan et al., 2011). Therefore, future scientists should be equipped with sufficient knowledge of green chemistry to support sustainable development (Cummings, 2013; UNEP, 2019).

1.1.2. Sustainable chemistry

Around the time green chemistry emerged in the USA, the term "sustainable chemistry" was coined by the Organization for Economic Co-operation and Development (OECD). The term became widely used in Europe (Carra, 1999; Hutzinger, 1999). Sustainable chemistry is described as:

> … a scientific concept that seeks to improve the efficiency with which natural resources are used to meet human needs for chemical products and services. Sustainable chemistry encompasses the design, manufacture and use of efficient, effective, safe, and more environmentally benign chemical products and processes. (OECD, 2020, para. 3)

Sustainable chemistry highlights minimizing pollution risks during chemical production. It also attempts to bring processes to a sustainable level by simultaneously looking at the aspects of ecological friendliness, economic growth, and overall quality of life (Centi and Perathoner, 2003). Sustainability also introduces innovation into the design of new chemicals, production processes, and technologies (OECD, 2020). Sustainable chemistry is seen to differ from green chemistry and is described as:

> … the maintenance and continuation of an ecologically-sound development whereas Green Chemistry focuses on the design, manufacture, and use of chemicals and chemical processes that have little or no pollution potential or environmental risk and are both economically and technologically feasible. (Hutzinger, 1999, p. 123)

Sustainable chemistry in its original interpretation views chemistry's contribution to sustainability as more than just green chemistry (Cummings, 2013). Both concepts, however, form a new philosophy of chemistry with different traditions (Centi and Perathoner, 2009). That is why both traditions were integrated and the term "Green and Sustainable Chemistry (GSC)" was proposed (Eilks and Zuin, 2018a). This represents an eco-reflective way of performing chemistry which is embedded in society (Eilks et al., 2017).

1.1.3. Green and sustainable chemistry education (GSCE)

Green and sustainable chemistry education (GSCE) incorporates the principles, ideas, and contents of GSC into chemistry education (UNEP, 2019). GSCE aims to design suitable options which incorporate GSC thinking into all broader educational areas - curriculum development, teaching, learning, and outreach. This stretches across the spectrum from in-class activities to laboratory experiments and the dissemination of GSC information to the public (Wang et al., 2018). It is increasingly important that chemistry curricula include GSC ideas, starting at the secondary schooling level (Burmeister et al., 2012). It is here where students start to develop a profound background of and opinions about chemistry. It has also been suggested that students should develop their thinking abilities with a strong plasticity for a more sustainable future (Caruana, 2015).

Studies have shown that GSCE courses can enhance students' critical thinking, problem-solving, and communicative skills. This is necessary to understand sustainable development both locally and globally (Parrish, 2007). Students felt empowered to address environmental problems and stated that GSCE had boosted their interest and motivation to learn chemistry. They were particularly interested in the practical side of GSC and had developed a more positive view of chemistry (Caruana, 2015; Haack et al., 2005). It is, however, that there still is debate whether GSCE should be concentrated or even restricted to certain courses and programs, or whether it should permeate all domains of teaching and learning chemistry (Zuin et al., 2021). We suggest the latter, or even the latter combined with additional learning opportunities on the philosophy behind GSCE.

GSCE has also been suggested as an excellent way to attract bright students to chemistry professions (Anastas and Beach, 2009). Sustainability offers a context for learning chemistry which is rich in possibilities that connect with students (Eilks and Hofstein, 2014). This includes both their personal interests and priorities, and aids with the challenges they will later face as they enter society, first as adolescents, then as adults (Fischer, 2012). As one way to introduce GSCE in secondary chemistry education, the concepts of relevance and socio-scientific issues (SSI) have previously been emphasized (Stuckey et al., 2013). SSIs are real-world issues that are socially significant, rooted in science and generally connected to approaches of systems thinking, which is holistic thinking highlighting the interdependence and interactions of the components of the chemical system with others (e.g., Mahaffy et al., 2018). SSIs are connected to social aspects comprised of political, economic, ethical, and humanistic factors (Klosterman et al., 2011). SSIs

have already increasingly become a prominent factor in contemporary chemistry education (see the overviews, e.g., in Eilks and Rauch, 2012; Eilks and Zuin, 2018b; Obare et al., 2020; Zuin and Mammino, 2015) and systems thinking was suggested a central skill for coping with them, e.g., by IUPAC (2017).

The role GSC plays is maintaining the current standard of living, while simultaneously bettering the economy towards a more sustainable future (Burmeister and Eilks, 2012). Burmeister et al. (2012) identified four models for implementing GSCE in formal education. These include: *(1) The adoption of green chemistry principles into science education laboratory work; (2) The addition of sustainability strategies as content in chemistry education; (3) The inclusion of SSI as contexts for guiding chemistry teaching and learning; and (4) Applications of sustainable chemistry as a part of ESD-driven institutional development.* Furthermore, Jegstad and Sinnes (2015) have modified Burmeister et al.'s (2012) original model. They have suggested a refined model for planning GSCE. This is represented by five ellipses which encompass five different categories (Fig. 1) ranging from chemistry content knowledge at the core to ESD employed in the practice of chemistry education. The categories represent different aspects of a complex whole and partly overlap to achieve a holistic perspective of GSCE.

2. Background for GSCE in the case of mainland China

2.1. The international background of GSCE

In 1996, the United States Environmental Protection Agency (EPA, 2017) started the annual Presidential Green Chemistry Challenge Awards in order to promote green chemistry innovation in academia and industry. There were 109 winners in the first 21 years. The winning technologies eliminated roughly 17 billion pounds of hazardous chemicals and solvents in the United States. This award program has since been replicated in other nations, including the European Sustainable Chemistry Award created by the European Union. Several peer-reviewed journals centering around GSC have also been established, such as *ACS Sustainable Chemistry & Engineering*, *ChemSusChem*, *Green Chemistry* or *Sustaibale Chemistry and Pharmacy*. These publications have widely advanced the development of GSC research (Chanshetti, 2014; Manley et al., 2008).

Many GSCE research programs were explored for secondary education based on outreach efforts by college students, educators, scientists, and organizations in the United States. Examples include the *Green Chemistry Education Network* (GCEdNet, 2020) launched by Gordon College, the non-profit organization *Beyond Benign* (2020), and the *Green Chemistry Institute* of the American Chemical Society (ACS, 2020). These programs were dedicated to developing and implementing good GSCE practices, including abundant online teaching and learning resources (Anastas and Beach, 2009; Byrne, 2000; Kennedy and Chapman, 2019). Most programs also contain practical work activities built upon inquiry-based learning principles (e.g., Cannon et al., 2020; Duangpummet et al., 2019).

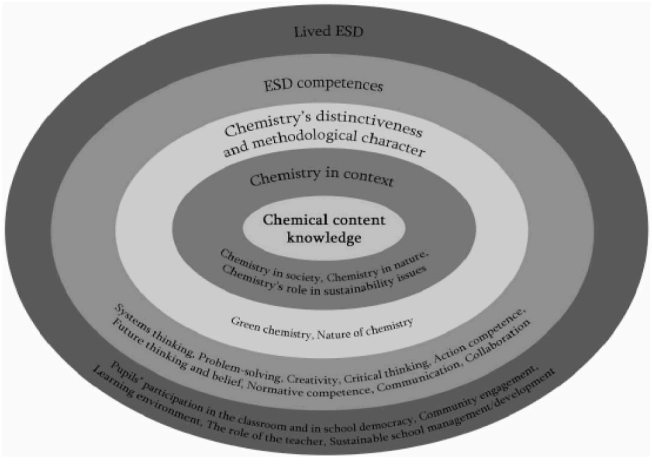
Lived ESD
ESD competences
Chemistry's distinctiveness and methodological character
Chemistry in context
Chemical content knowledge
Chemistry in society, Chemistry in nature, Chemistry's role in sustainability issues
Green chemistry, Nature of chemistry
Systems thinking, Problem-solving, Creativity, Critical thinking, Action competence, Future thinking and belief, Normative competence, Communication, Collaboration
Pupils' participation in the classroom and in school democracy, Community engagement, Learning environment, The role of the teacher, Sustainable school management/development

Fig. 1. A model for ESD in chemistry education suggesting chemical knowledge to be embedded into context, scientific methodology, sustainability competencies and lived ESD (Jegstad and Sinnes, 2015).

In Europe, one project of the Chemistry Is All Around Network (2020), which is funded by the European Commission, provided green chemistry teaching resources including experiments to secondary schools. Other GSCE programs or research studies include Greener Industry (2020) in the United Kingdom, chemical industry case studies in Israel (Hofstein and Kesner, 2006), and environmentally-oriented chemistry experiments (Bader, 1992; Bader and Blume, 1997), models and case studies in Germany (Eilks, 2002; Linkwitz and Eilks, 2020). In Germany, one of the objectives stated in the national science standards (The Standing Conference of the Ministers of Education and Cultural Affairs of the Federal Republic of Germany [KMK], 2004) is to nurture students' ability to communicate and form ideas about science research and technology evaluation (Burmeister and Eilks, 2012). In a word, GSCE in secondary education in Western countries has begun to develop. The process is supported by university education researchers and related agencies. It is consistent with Deng's (2010) opinion that institutional and program curricula are more easily and effectively carried out than top-down implemented curricula options.

2.2. The educational policy background for GSCE for mainland China

China has begun to play a more prominent role in the global community due to its large population and rising economic growth. However, this development also entails environmental pollution problems and gradually decreasing levels of natural resources. In order to be a responsible country, China has attempted to smoothly and practically develop ESD by means of national policies (Wang et al., 2018). "China's Agenda 21" was officially drafted by the Chinese government in 1994 along the lines of Agenda 21 by the UNCED. The strategies of sustainable development and rejuvenating China through science and education have been the basic national policies for economic and social development in China since 1996 (China National People's Congress, 1996). In 1997, green chemistry was first highlighted in *the 72nd Xiangshan Science Conference* by China's Ministry of Science and Technology. The main theme was "the challenge of sustainable development to green chemistry". In 1998, the first international workshop on green chemistry in China (1st IWGC) was held by the University of Science and Technology of China (USTC). Then *Chemistry*, one of the leading Chinese chemical journals, published a special issue called *Green Chemistry and Technology*. An initial course in green chemistry at USTC was also launched (Min, 2001; Wang et al., 2018). After this, GSC research activities rapidly increased and green chemistry courses were gradually opened by more universities. These were popularized by the establishment of several research institutes and centers of green chemistry, and by the publication of several green chemistry (experiment) textbooks in China (Anastas and Kirchhoff, 2002; Cui et al., 2011; Matus et al., 2012; Tundo et al., 2000; Wang et al., 2018). GSC also profited from increased public awareness and new regulations issued by the Ministry of Environmental Protection built in 2009 (Matus et al., 2012). The Chinese Chemical Society (CCS, 2020) in cooperation with Elsevier held a big conference in Beijing called *Green China 2019:* 1st *International Green and Sustainable Chemistry Conference*. The conference summarized the latest GSC developments in 2019. This shows that the CCS started to concern itself with the Agenda 2030 goals listed by the UN.

In the 2018 Program for International Student Assessment (PISA), a representative international assessment of science study, four cities and provinces in China (Beijing, Shanghai, Jiangsu, and Zhejiang) participated and received top marks in student science performance. Chinese science education attracted international attention including its teacher-

centered, textbook-dependent, and examination-oriented features with hardworking, disciplined, and teacher-relied students in the Confucian culture (Lo, 2019; Yeung, 2015). Education in grades 1–9 is compulsory in China. Upper secondary education in grades 10–12 is comprised of vocational and general education. In 2019, the graduation ratio of junior secondary school graduates was 95.5% (the Ministry of Education of the People's Republic of China [MOE], 2020). The basic education system in China is centralized by the government. Textbook publishing, teaching, learning, and assessment are all guided by the national curriculum standards of the MOE. However, Shanghai uses local curriculum standards, since it is a leading city of educational reform. The *Shanghai Secondary School Chemistry Curriculum Standards* (Shanghai Municipal Education Commission, 2004) emphasizes the utilization of ideas of green chemistry, by general, inquiry and outreach courses using multiple learning and teaching approaches. It aims to assist students to understand environmental problems and to focus on the significance of harmony between human beings and nature.

In the previous version of the *Chemistry Curriculum Standards for High Schools (experimental version)* (MOE, 2003), which is based on scientific literacy, the topic of sustainable development was mentioned and shown in some modules of chemistry content (Bodlalo et al., 2013). The current *Chemistry Curriculum Standards for High Schools (the 2017 version)* (MOE, 2018) focuses on five core competences: "macroscopic identification and microscopic analysis, changes and equilibrium, evidence-based reasoning and modeling, scientific inquiry and innovation, and scientific attitude and social responsibility". It refers to the concept of green chemistry and highlights GSCE, including related evaluation. Its stated educational goals include fostering students' awareness of green chemistry and sustainable development. They also wish to develop a deep understanding of the relationship between chemistry, society, and the environment. For the core competence of scientific attitude and social responsibility, it requires students to:

> … have awareness of sustainable development for saving energy and protecting the environment; to form an appropriate, green low-carbon and lifestyle; to make correct value judgments about chemistry-related, hot social issues; to attend social practice activities about chemical issues. (MOE, 2018, p. 5)

According to Jegstad and Sinnes (2015), the implementation of GSCE is suggested having potential to comprehensively achieve the core competences of the current chemistry curriculum standards in China.

2.3. The place of mainland China in the international scene of GSCE research

To get an initial overview of international GSCE research, 532 publications were identified by searches on the topics of "green chemistry education" (GCE) or "sustainable chemistry education" (SCE) taken from the Web of Science Core Collection since 1991 (results retrieved on September 3, 2020). The numbers are for our own searches and differ slightly from those published in UNEP (2019, p. 517). The search terms may have been used slightly differently than in the first study and the date of the second search was more than a year later. The overall picture remains, however, the same.

The number of papers examining these topics increased steadily over the last 20 years (Fig. 2), especially since the year 2010. This indicates that GSCE is gaining increasing attention in the international literature. Of the identified papers, a total of twenty-one stem from China, which is in seventh place internationally in quantitative terms. This remains, however, far less than the 213 papers published in the USA and the 45 papers stemming from Germany. Compared with chemistry research about GSC, GSCE papers produced by Chinese chemistry education researchers have much less international influence and lag behind the USA and Germany. That is why this paper investigates the current state of the GSCE literature from mainland China to provide an effective and feasible path or model to improve GSCE in China, especially in the case of secondary education.

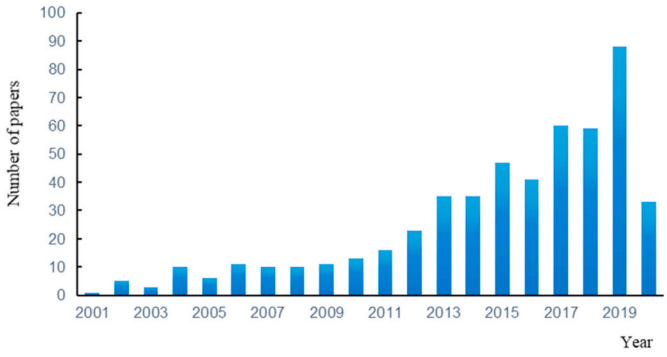

Fig. 2. The trend in the number of international leading papers published with topics concerning GCE or SCE during the last 20 years based on the Web of Science (2020 covers only the entries of the first 8 months).

3. Research questions

This literature review aims to answer the following questions.

- What is the status quo of GSCE in the chemistry education literature from mainland China?
- What are the main foci in the GSCE literature in mainland China?
- What is the connection between secondary and tertiary GSCE in mainland China?

This study focuses on mainland China. Taiwan, Hong Kong, and Macao are not included, because they have different educational traditions and different political and educational systems.

4. Method

4.1. Data collection

To screen the existing information about GSCE research in mainland China, we used searches from the Web of Science, Google Scholar, and ERIC (Education Resources Information Center). Search keywords were "green chemistry education", "sustainable chemistry education" and "socio-scientific issues". The latter term was considered based on the suggestion given in Burmeister et al.'s (2012) model of GSCE. It is clear, however, that not all papers identified by this search and labelled by corresponding terms were fully in line with contemporary understandings of "green chemistry education", "sustainable chemistry education" or "socio-scientific issues" from a theoretical point of view. To avoid a too great bias, all relevant papers were read and some papers were excluded "by hand" if there was an obvious mismatch with the search term intentions. The search was then reduced to papers from mainland China in these databases with an "in chin*" search and then by hand. Data was collected on October 13, 2020. The number of publications is shown in Table 1. There are some overlaps in papers of the above databases, and finally, around 20 target papers were identified (Table 1).

For issues of language use and specific local needs and concerns, English-language journals do not comprehensively necessarily represent Chinese chemistry education research and practices. Especially practical contributions might likely be more covered by local journals in China (Song et al., 2016). Thus, we explored more data in the most popular Chinese academic database: China National Knowledge Infrastructure (CNKI). Four leading journals of Chinese chemistry education in mainland China were identified: *Chinese Journal of Chemical Education* (*CJCE*), *Education in Chemistry* (*EC*), *Teaching Reference for Middle School*

Table 1
GSCE research publications in China based on international databases.

Database	Number of publications and methods	Categories of representative papers
Web of Knowledge	34 hits for "green chemistry education in chin*" OR "sustainable chemistry education in chin*", with 3 target papers in mainland China (by topics from all databases of the Web of Science); 10 hits for "socio-scientific issues in chin*", 5 hits refined by relation to chemistry education in mainland China (by topic from all databases of the Web of Science).	• Review about GSCE in China (tertiary education) Cui et al. (2011); Matus et al. (2012); Wang et al. (2018) • Curriculum analysis (secondary education) Bodlalo et al. (2013) • Practical work in teaching (tertiary education) Cai et al. (2013); Li et al. (2011); Lu et al. (2017); Xie et al. (2016); Wang et al. (2010a); Zhou et al. (2018); Zhu et al. (2008) • Teaching by lectures (tertiary education) Song et al. (2004) (exercises); Haxton and Darton (2019) • SSI (secondary education) Sternäng and Lundholm (2011; 2012); Wan and Bi (2020) • Students' awareness (secondary education)Lin (2017); Ma and Hu (2020); Zhu (2019)
Eric	288 hits for "green chemistry education" (peer-reviewed only), 7 hits refined by the location of mainland China; 120 hits for "sustainable chemistry education" (peer-reviewed only), 2 hits refined by the location of mainland China; 261 hits for "socio-scientific issues" (peer-reviewed only), 3 hits refined by relation chemistry education in mainland China	
Google Scholar	806.000 hits (excluding citations) for "green chemistry education in China", with 2 target papers by relevance; 191.000 hits (excluding citations) for "sustainable chemistry education in China", with 3 target papers by relevance; 2.210 hits (excluding citations) for "socio-scientific issues in China", 8 hits refined by relation chemistry education.	

Chemistry (*TRMSC*), and *University Chemistry* (*UC*). These journals were recognized as the first batch academic journals by the State Administration of Press, Publication, Radio, Film, and Television of the People's Republic of China in 2014. *CJCE* is a core, semimonthly journal held by CCS and Beijing Normal University since 1980. *EC* is a core, monthly journal published by East China Normal University since 1979. *TRMSC* is a popular, semimonthly journal focusing on secondary chemistry education and put out by Shaanxi Normal University since 1972. Additionally, *UC* is a popular monthly journal for chemistry teachers. It promotes tertiary chemistry education reforms and is issued by Peking University and CCS since 1986. Before 2016 it was published bimonthly.

The search keywords used in CNKI are very similar to the international search mentioned above, but reflect slight changes to match the local context. Based on the initial search in CNKI, the keyword "sustainable chemistry education" was found not to be used by Chinese chemistry educators or teachers. Therefore it was replaced by "sustainable development and chemistry education". To obtain enough target journal papers, on October 28, 2020, the authors searched CNKI for "green chemistry", "sustainable development", and "socio-scientific issues" by topic in the above-mentioned four Chinese chemistry education journals. A further search focused on "green chemistry education", "sustainable development and chemistry education", "socio-scientific issues", "green chemistry and education", and "green chemistry and chemistry education" by topic in the other Chinese academic journals of CNKI excluding the above four journals. The beginning search of the first three terms resulted in limited hits, so the keywords were supplemented by the other two terms to give more hits. The detailed data from searches using the corresponding search terms combined with the Boolean operator "OR" (retrieved on October 28, 2020) are shown in Table 2. This includes the number of target papers refined by relation to GSCE in the summaries and representative papers. Finally, a total of 1024 target papers were identified by CNKI, ranging from the year 1997–2020.

Table 2
GSCE research papers in CNKI.

Search terms	Journals	Number of hits (refined to GSCE)	Representative papers with categories
"green chemistry" OR "sustainable development"	*CJCE*	143 (110)	• Introduction of international GSCE Cai (2016); Hu et al. (2003); Pei et al. (2018); Xue (1997a) • Secondary GSCE: Teaching strategies Dong and Yang (2002); Sui (2010); Zhang and Tan (2009); Ye et al. (2018) *Experiment teaching* Liu and Liu (2012); Lv (2007); Wu et al. (2011); Wu et al. (2009); Zhao (2013) *Lecture teaching* (Fan et al., 2020; Li and Fang, 2019; Sun et al., 2020; Wang and Zhang, 2019) (SSI); (Yang, 2018) (exercises) *Textbooks* Bai (2005); Yang et al. (2013) *Students' and teachers' awareness* Gu and Wang (2019); Qiu and Ma (2009); Zeng and Li (2013) • Tertiary GSCE: *Teaching strategies* Du et al. (2009); Xu et al. (2016); Xie et al. (2006); Zhang et al. (2019); Zheng and Zhou (2017) *Lecture teaching* Li and Cao (2015); Xue et al. (2016); Yu et al. (2008); Zhan et al. (2010) *Outreach activities* Chen et al. (2014); Yan et al. (2011) *Experiment teaching* Cao et al. (2010); Lin et al. (2020); Wang et al. (2010b); Yan et al. (2018) *Students' awareness* He et al. (2013); Qiao et al. (2013)
	EC	68 (49)	
	TRMSC	109 (70)	
	UC	54 (31)	
	Others	910 (752)	
"green chemistry education" OR "sustainable development and chemistry education" OR "green chemistry and education" OR "green chemistry and chemistry education"			
"socio-scientific issues"	*CJCE*	3 (2)	
	EC	5 (4)	
	TRMSC	8 (4)	
	UC	0 (0)	
	Others	35 (2)	

4.2. Analysis

International journal articles about GSCE research in China are quite rare. So, we decided to just present the data with illustrative examples, and to further employ them in the discussion about publications within mainland China. A broader picture of what is occurring within mainland China is based on the CNKI data. This data was subject to further analysis. Citespace 5.7. R2 software was used as a tool to identify trends in authorship, institutes, and keywords. (The software and instructions are available online at http://cluster.cis.drexel.edu/~cchen/citespace/.) The time-span setting in the Citespace is from 1997 to 2020, and every one year is as a time zone for the analysis. Due to the limited number of defined papers, the analysis started with the threshold settings of c

(citation), cc (co-citation), ccv (cosine coefficient) parameters with 1, 1, 20; 1, 1, 20; 1, 1, 20, (20 is the default number of ccv). Each paper was accounted with a comprehensive result, and then checked by settings of c, cc, increased by 1 until the produced visualization gained high centrality, valid and high modularity ($Q > 0.3$) and a weighted mean silhouette ($S > 0.5$). Other settings were default. Due to the still limited number of findings, this review should not be understood presenting a quantitative picture or research. Even if the paper reports the numbers of hits, interpretations should be understood on the level of trends and interpretations. For further qualitative interpretation, key papers were identified and inductively mapped to essential features of the teaching and learning of chemistry. From the key papers, prominent foci were identified and highlighted.

5. Findings

5.1. Trends in the GSCE research literature in mainland China

Using only international journal publications, there is only a quite limited number of papers dealing with GSCE in mainland China (see Table 1). The focus tends to mainly be on green chemistry experimental teaching, reviews of GSCE for tertiary education, SSI-based GSCE teaching, or the investigation of students' awareness of GSCE in secondary education. From the distribution of 1024 total target papers from CNKI (see Fig. 3), we can see that GSCE gradually started attracting more researchers' attention in the 2000s and stabilized around the year 2005. This differs from the continued growth of international GSCE research papers as shown by Fig. 2. The authors and their institutes in the 1024 CNKI papers were analyzed with the help of Citespace 5.7. R2 on November 2, 2020. The most productive authors in terms of publications were Xiaohua Cao and Yulong Shen, who each produced seven papers. The most productive institute in terms of numbers was Tangshan Normal University with a total of nine papers (see Table 3). Of the most productive institutes, most are normal universities. Co-authorship analysis using Citespace (the resulted clustering analysis with $Q = 0.9939$, $S = 1$) identified Xiaohua Cao as the most active writer to cooperate with others in terms of numbers. These papers make up a co-author community with Yulong Shen, Aixin Huo, and Lihua Liu. Co-institute analysis by Citespace (clustering analysis with $Q = 0.978$, $S = 1$) revealed Beijing Normal University to be the most active cooperator with other institutes or high schools in terms of publications, followed by the Jiujiang University College of Chemistry and Chemical engineering. This means that there is no single, representative community for GSCE research in China, even though some level of cooperation between authors and institutes exists.

With the Citespace threshold settings of c, cc, ccv 1, 1, 20; 1, 1, 20; 3, 3, 20, 17 resulting clusters (resulted clustering analysis with $Q = 0.6228$, $S = 0.8768$) were found in terms of keywords co-occurrence of log-likelihood ratios for the 1024 CNKI papers, including the top five terms in each cluster (see Table 4). There were many overlaps between

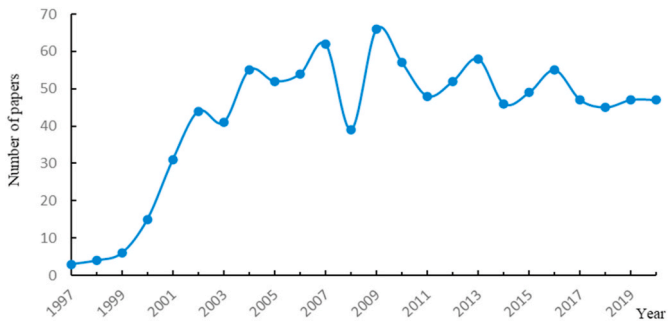

Fig. 3. The trend in published papers on GSCE from China based on CNKI for the years 1997–2020.

Table 3
Top 10 productive authors and institutes about GSCE in quantitative terms from China based on CNKI.

Rank	Authors	Count	Begin	Institutes	Count	Begin
1	Xiaohua, Cao	7	2005	Tangshan Normal university, Department of Chemistry	9	2005
2	Yulong, Shen	7	2009	Inner Mongolia Vocational College of Chemical Engineering	7	2012
3	Zhicheng, Ma	6	2003	Jiujiang University, College of Chemistry and chemical engineering	7	2009
4	Aihua, Huo	5	2003	Henan University, College of Chemistry and chemical engineering	6	2007
5	Jun, Li	5	2002	Beijing Normal University, College of Chemistry	5	2014
6	Lihua, Liu	5	2007	Huainan Normal University, Department of Chemistry and chemical engineering	5	2009
7	Guoqing, Zhong	5	2006	Wuhan University, College of Chemistry and Molecular Science	4	2010
8	Lixin, Deng	5	2001	Xinyang Normal University, College of Chemistry and chemical engineering	4	2007
9	Yong, Wu	5	1998	Anhui Normal University, College of Chemistry and Material Science	4	2009
10	Weiquan, Cai	4	2003	Hubei University, College of Xing and Zhi, Department of Biological Engineering	3	2012

the clusters. The clusters illustrate how broad any connections in teaching towards GSCE are addressed. It is clear, however, in the same time that the many clusters might imply that many papers are connected with GSCE, but are not taking its underpinnings and central aims into account with sufficient theoretical depth. The hot-button topics are organized in four categories: green chemistry experiments (teaching), the introduction of green chemistry content (education), teaching methods and reform, and chemistry textbooks. The keywords presented in Fig. 4 show that frequent keywords emerge during specific years on the time line of GSCE research in China. In the 2000s, the environmental pollution and green education were highlighted. Since 2015, green chemistry ideas were added strongly to the discussions, followed, e.g., by aspects of high school chemistry and teaching reform. SSI-based education is a new discussion area since 2018. It presents a new stage of GSCE in China.

5.2. Foci of main emphasis in the secondary GSCE academic literature in mainland China

5.2.1. Focus 1: introduction of international GSCE to mainland China

The development of GSCE for secondary chemistry education in China used the same lines as the introduction of GSCE in Western countries since the late 1990s. Xue (1997a; 1997b) first introduced green chemistry and the *Presidential Green Chemistry* Award of the

Table 4
Top-ranked clusters table of keywords co-occurrence network about GSCE research in China.

Cluster	Size	Mean (Year)	Top five terms (log-likelihood ratio)
0	114	2007	**Practice**, teaching reform, infusion, teaching, experiment
1	101	2005	**Chemistry textbook**, chemistry teaching, textbook reform, low-carbon lifestyle, medical and higher vocational education
2	88	2005	**Microscale chemistry experiment**, environmental protection, undergraduate students, pharmaceutical engineering, crystallization
3	68	2004	**Green chemistry education**, atom utilization, green chemistry, chemistry elective course, non-polar molecules
4	64	2008	**Teaching by experiments**, green chemistry course, teaching method, inorganic chemistry experiment, basic chemistry experiment
5	53	2007	**Pollution**, chemical laboratory, microscale experiments, chemistry experiments, improved experiments
6	51	2005	**Chemistry experiment teaching**, sulfur dioxide, green, broken test tubes, sustainable development
7	47	2003	**Introduction of achievements**, the Presidential Green Chemistry Award of the United States, organic solvents, atom economy, synthetic routes
8	46	2005	**Principles of green chemistry**, electrochemical industry, comprehensive exercises, outreach course
9	41	2005	**Butyl acetate**, green chemistry experiment, chemical engineering major, environmental materials, environmental protection issues
10	36	2007	**Organic chemistry experiment**, no solvent, comprehensive experiment, innovative abilities, environmentally benign chemistry
11	31	2007	**Toxic gas**, disposable syringe, sodium hydroxide solution, pipe orifice, cotton balls
12	16	2005	**Chemistry**, humanistic education, science education, psychological growth, individual motivation
13	15	2006	**Nitric acid**, oxidation number, constructing knowledge, chemical equation, Nitrogen, compound
14	12	2008	**Collaborative learning**, pharmaceutical Engineering, KAQ (Knowledge-Ability-Quality) teaching model, teaching practice, green chemistry
15	12	2004	**Organic chemistry experiment teaching**, water pump, environment knowledge, organic chemistry laboratory, green chemistry,
16	7	2008	**Low-carbon lifestyle**, chemistry, literacy, undergraduate students, higher education of engineering

United States in the publication *CJCE*. These reports were updated and other famous awards for green chemistry research from other countries were also presented (Hu et al., 2003; Pei et al., 2018). Related teaching resources such as textbooks, journals, institutes, and websites on Western GSCE were introduced as well (Cai et al., 2003). Tertiary green chemistry education from leading international universities (Shen et al., 2010; Shen and Wang, 2006) was also presented as one reference point for Chinese GSCE. Cai (2016) pointed out the measures suggested for secondary school GSCE by *Beyond Benign* of the United States. These included encouraging society agencies' participation in GCE, the construction of systemic lesson plans, enhancing the training of teachers about green chemistry, and carrying out extracurricular activities.

5.2.2. Focus 2: Teaching strategies for secondary GSCE

Several strategies for teaching GSC were identified for secondary GSCE in mainland China. One major focus is on integrating GSC into the classroom with the help of practical work by actively conducting inquiry-based learning in real contexts. Further suggestions are to provide extracurricular activities centered around GSCE, employ modern educational technologies, and utilize other societal organizations or universities (Dong and Yang, 2002; Li, 2004; Xu, 2004). Research also reported on ways to deal with the problem that teachers lack the appropriate teaching strategies for secondary GSCE and that students have low levels of GSC understanding. Ye et al. (2018) have suggested that teachers should integrate and structurally present agricultural and industrial technologies from real life using GSC with multifaceted views to motivate students' learning. Carrying out specific events or outreach activities based on GSC, such as lectures on green chemistry, poster exhibitions, green chemistry competitions, and visiting related industries or plants, has also been mentioned for GSCE (Yang et al., 2013).

5.2.3. Focus 3: Practical work

Besides teaching methods, another major focus was finding ways to change practical work. Chemistry practical work can motivate students' learning, assist students in understanding theories, and allow learners to attain practical ability with the scientific method (Woolnough and Allsop, 1985). Zhang and Tan (2009) also highlighted changes towards GSCE-based practical work: choosing different chemicals, designing green chemistry experiments based on chemistry curriculum standards and green chemistry, popularizing microscale chemistry experiments, and emphasizing the application of green chemistry experimental procedures. Other discussions have included the improvement of experimental equipment (Li, 2004), an emphasis on the whole procedure of experimental designs with environmental-friendly ideas (Dong and

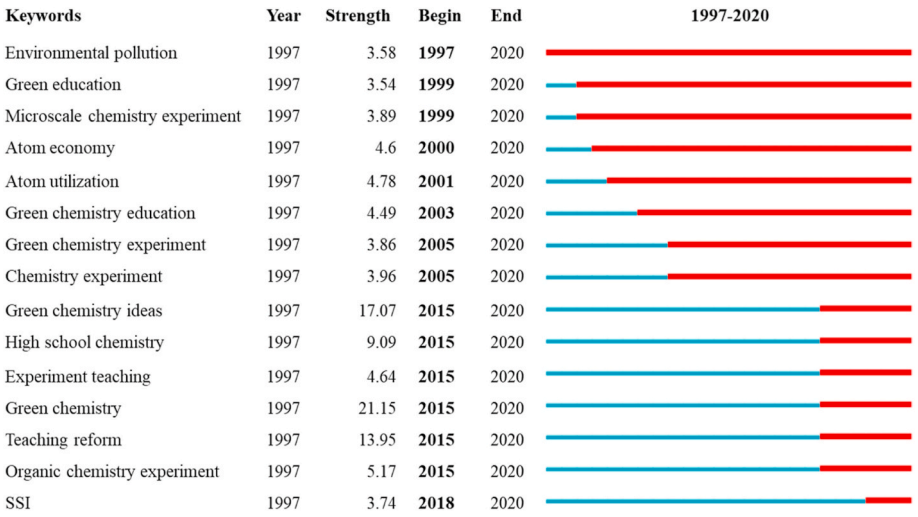
Keywords Year Strength Begin End 1997-2020
Environmental pollution 1997 3.58 1997 2020
Green education 1997 3.54 1999 2020
Microscale chemistry experiment 1997 3.89 1999 2020
Atom economy 1997 4.6 2000 2020
Atom utilization 1997 4.78 2001 2020
Green chemistry education 1997 4.49 2003 2020
Green chemistry experiment 1997 3.86 2005 2020
Chemistry experiment 1997 3.96 2005 2020
Green chemistry ideas 1997 17.07 2015 2020
High school chemistry 1997 9.09 2015 2020
Experiment teaching 1997 4.64 2015 2020
Green chemistry 1997 21.15 2015 2020
Teaching reform 1997 13.95 2015 2020
Organic chemistry experiment 1997 5.17 2015 2020
SSI 1997 3.74 2018 2020

Fig. 4. Top 15 keywords with the strongest citation bursts about GSCE research in China based the database CNKI from 1997 to 2020 (red lines indicating the years the key term is highly used).

Yang, 2002), and the combination of multiple or comprehensively-designed experiments (Sui, 2010).

The improvement of green chemistry experiments plays an important part in secondary GSCE research in the acadmic papers identified from mainland China. Generally, three dimensions could be identified, namely the use of green raw materials, the implementation of microscale experiments, and the improvement of devices for existing experiments already required by textbooks or curriculum standards. Many suggestions have already been made for choosing more environmentally-benign materials. For example, using low-cost calcium oxide with a controllable experiment instead of calcium hydroxide was proposed for experiments synthesizing and examining the properties analysis of ammonia (Lv, 2007). Silica has been suggested as a replacement for the solvent chloroform in the addition reaction of ethene and bromine (Wu et al., 2011). The decomposition reaction of ammonium hydrogen carbonate as an endothermic reaction has replaced the reaction of barium hydroxide solid with ammonium chloride (Wu et al., 2009). The recycling of ammoniacal copper solution (Schweitzer's reagent) waste was employed to prepare copper (II) sulfate crystals (Liu and Liu, 2012). Microscale experiments have also been highlighted as a way to save on the cost of materials, reduce overall material consumption, and decrease environmental pollution. Examples of this include extracting and identifying iodine from kelp on spot plates (Ma and Chen, 2017), the microscale electrolysis of water, and a fuel cell made of hydrogen and oxygen in V-shaped and U-shaped devices (Zhao, 2013).

Last but not least, improved laboratory set-ups have been proposed. For example, experiments were designed to deal with toxic gases. Sealed devices were designed to carry out bleaching experiments with sulfur dioxide. They were also used for the reaction of copper with nitric acid (Sui, 2010; Yang et al., 2006). Combined devices were constructed to handle the combustion reactions of white phosphorus, red phosphorus or sulfur in air (Fu, 2013). And multifunctional devices were conceived for the production and testing of research experiments on the properties of toxic gases, such as sulfur dioxide, ammonia, and chlorine (Xie et al., 2010a, b). However, many papers still hold tightly to the traditional experiments suggested by the educational standards, instead of completely replacing them with alternatives based on arguments from GSC.

5.2.4. Focus 4: curriculum, SSIs and assessment

Suggestions for curriculum betterment have also been made. These argue for teachers providing more certain contexts of GSC and using appropriate teaching methods, so that their classroom teaching becomes more than content learning based on experiments. E.g., Sun et al. (2020) integrated learning about waste water treatment using a live, virtual visit to a waste water treatment plant. The visit included a live technician, a simulated experiment, and a role-playing discussion in order to foster students' awareness of green chemistry and societal responsibility. Wang and Zhang (2019) designed a course on environmental protection and green chemistry. They based their unit on content analysis of chemistry textbooks with an eye on the core competencies of scientific attitude and social responsibility. Due to the exam-orientated Chinese schooling system, green chemistry exercises have also started to play a role in green chemistry education research. College entrance examinations are one of the primary drivers of Chinese secondary education. They have always consisted of multiple choice tests or simple fill-in-the-blank answers since the year 2000 (Wang, 2001). Recently, however, some green industrial process problems were added to the list (Yang, 2018). This might compel chemistry teachers to be more concerned about teaching green chemistry ideas. Yang (2018) provided the context of coal-burning. The example combined an adapted green chemistry exercise on absorbing exhaust gas from one college entrance examination. This was tied to a class activity for grade 12, in which students carried out a group discussion to develop their core chemistry competences. The researcher found that their awareness of green chemistry had increased in the post-unit interview.

Aside from the above examples infusing GSC into content, practices and exercises, implementing SSI about GSCE is also a new concern. As we mentioned previously, research on SSI in mainland China is still in the initial stages. But recently some in-service science teachers have started paying more attention to SSI (Chen and Huang, 2020). Wan and Bi (2020) raised six potential fields of SSI topics for science teaching with the use of questionnaires among related experts. The topics included: environmental issues, safety and health, resources and energy, ecological systems, biotechnology, and new materials. All of the fields provide opportunities to be connected to GSCE. The researchers also suggested including local problems in classroom discussions. Likely candidates were traffic restrictions due to smog, the building of a sulfuric acid plant, and the operation of a paraxylene program (Chen, 2017; Fan et al., 2020; Li and Fang, 2019; Luo et al., 2020). The teaching model aims at engaging students with an SSI. This should deal with related problems in which groups of students discuss related materials. Available tools include role-playing, decision-making and reflection exercises, watching demonstrations, or carrying out related inquiry-based experiments guided by teachers. All of the documented cases showed positive results supported by accompanying reflections. Some of them were also proven to better students' argumentation abilities. Chen et al. (2019a, b) analyzed scientific risk contents in the 2012–2016 high school chemistry course plans in Jiangsu province. They found that teachers paid more attention to the contextual integration of SSIs, but lacked focus on argumentation and thinking on uncertainty and risk in science.

Due to the importance of ethical aspects in the Chinese cultural context, researchers also paid attention to students' moral views as they discussed SSIs. Sternäng and Lundholm (2011) interviewed Beijing secondary school students about climate change and found that the students have different moral standpoints about SSIs when considering individuals (self versus others). The students were concerned about economic development and affluence, and thought the environmental issues are unavoidable (Sternäng and Lundholm, 2012). However, more research about students' related abilities, such as decision-making and argumentation, and teaching interventions based on SSI is still needed. Today, most school science teachers tend to emphasize science subject knowledge which closely influences their careers. However, they may ignore the role of SSI in nurturing students' ideas about social responsibility (Albe et al., 2014).

5.2.5. Focus 5: Textbooks

Due to many teachers' tendency to tightly cling to the textbook, GSC ideas in textbooks are considered to be the most important and direct resource for the implementation of GSCE. As of 2000, there are three versions of chemistry textbooks used in China. There have also been two new rounds of secondary school curriculum reform: the 2003 version of scientific literacy (MOE, 2003) and the 2017 version of core competencies (MOE, 2018). According to related research, green chemistry ideas have been found in recent versions of secondary chemistry textbooks. Although the GSC content remains limited, the latter version contains more GSC content and is more multifaceted in its methods of presentation. Bai (2005) found some green chemistry content in high school chemistry textbooks used before 2003, even though the concept of green chemistry had not yet been officially introduced. Yang et al. (2013) summarized contents and topics about green chemistry in the textbooks, which were used for the 2003 curriculum reform. However, they found that green chemistry ideas tended to cluster around environmental protection. The contents shown were discrete without an outline connected to any related concepts. They also tended to appear more often in elective modules, rather than in obligatory parts of the curriculum. Chen et al. (2019a, b) concluded in their study that environmental and sustainable development issues in chemistry textbooks from mainland China remain quite limited.

5.2.6. Focus 6: Teachers and students

Although the existing GSCE investigations into secondary school teachers and students are rare, the following finding is unequivocal: Chinese teachers and students generally have only a basic understanding of GSC. Due to exam-oriented assessment and limited support, their awareness of green chemistry remains weak. Many misunderstandings about green chemistry ideas still exist, especially in rural areas (Ma and Hu, 2020; Qiu and Ma, 2009; Xia et al., 2008; Yang and He, 2008). Questionnaires of students and teachers on GSC topics, such as low-carbon lifestyle or global warming, revealed that most students had heard about the concepts from public media. Their understanding of the related concepts had not been elaborated upon sufficiently by schooling, because many teachers lack the necessary teaching strategies and resources (Lin, 2017; Zeng and Li, 2013). Gu and Wang (2019) investigated high school students' competency in green applications using questionnaires based on high school chemistry content and features of green chemistry. They found green application competences fell in line with the levels of students' academic abilities without any gender differences. Similarly, Zhu (2019) found that Chinese secondary students' attitudes, including environmental awareness, interest, and epistemological beliefs, influence their scientific competencies without gender or urban differences, based on the analysis of the student questionnaire used in PISA 2015.

5.3. Fields of main emphasis in tertiary GSCE academic literature in mainland China

Compared to secondary GSCE in China, GSCE at universities or colleges shows a much more developed form. As there are many chemistry or science majors at the different universities, institutes, and colleges, the teachers generally tend to have stronger academic backgrounds and are more concerned about research and publishing. They are more able to find and try out green chemistry experiments and to get new ideas from international communities. Tertiary GSCE in mainland China is mostly implemented in courses about green chemistry or other subsubjects of chemistry permeated by green chemistry. Green chemistry courses are usually offered as public elective courses, so they take an important role in implementing ESD at Chinese universities. This is why there is a relatively narrow range of overall foci, and papers tend to deal with the details of carrying out GSCE.

5.3.1. Focus 1: Teaching strategies in tertiary GSCE

Many universities in China have offered green chemistry courses since the early 2000s. Many teachers now have experience in this area. For elective courses of general studies at universities, Zhang et al. (2019) suggested that teachers should offer reasonable content and use multidimensional assessment in green chemistry courses. Teaching methods, such as group discussions, video-scaffolding, flipped classrooms, and lectures with certain topics are also recommended. The utilization of exercises about green chemistry can also be a valuable method (Song et al., 2004). In chemistry sub-areas, such as organic, inorganic, or medicinal chemistry, researchers suggest integrating atom economy, green reagents, green reaction conditions, and green products, core ideas of green chemistry, and green chemistry study cases into their classrooms or practical work (Du et al., 2009; Jin and Xu, 2007; Xie et al., 2006; Xu et al., 2016). Other teaching strategies are considered as well, such as engaging with the latest research results and incorporating students' daily-life problems which are related to GSC. The use of extracurricular activities is also suggested (Li, 2016; Zheng and Zhou, 2017).

The implementation of tertiary GSCE based on classroom teaching is seen as more efficient with more modern information and communication technologies and when popular education ideas are used and discussed. Case study-based teaching is proposed in green chemistry courses. For example, students can search the internet and discuss related cases before teachers explain things in the classroom. Sound results can be supported by post-learning surveys (Xue et al., 2016). Zhan et al. (2010) raised several teaching methods for infusing GSCE ideas, based on the Knowledge-Ability-Quality (KAQ) teaching model. These included using modern educational and collaboration technologies, connecting textbooks and reference books, and constructing teaching evaluation systems. Yu et al. (2008) integrated the idea of GSC in chemistry courses and guided students in building a website on environmental protection to disseminate the idea of GSC. Haxton and Darton (2019) described a course with international group discussions between Chinese and English college students, which focused on GSC topics via an Internet platform. The education of student teachers is also considered to be important. Li and Cao (2015) constructed an inquiry learning model for a green chemistry course for student teachers. This was based on writing and presenting research papers on related topics of green chemistry topics in groups. It achieved positive results in students' self-evaluation after the exercise.

Real-life contexts have provided help to students when constructing new knowledge (Rannikmäe et al., 2020). Taking advantage of local resources or contexts about GSCE can be an effective way to contribute to ESD. One case study on green chemistry about the ecological protection of Poyang Lake was implemented into classroom teaching using practical work, on-site visiting activities, and summative evaluation for undergraduate students (Yan et al., 2011). Student internships in industry and participation in research work or competitions about green chemistry were also verified as effective methods for GSCE teaching (Chen et al., 2014).

5.3.2. Focus 2: Practical work

Practical work is an important and established component of Chinese tertiary chemistry education. It is usually implemented through separate laboratory courses in the chemistry-related fields. Ideas of GSC are discussed in almost all fields of chemistry teaching. Series of strategies for practical work infusing green chemistry have also been proposed. These include a broad spectrum of possibilities: selecting rational contents or experimental topics with environmentally benign raw materials, choosing alternatives procedures, solvents, catalysts, products, and by-products, selecting optimal synthesis routines using atom economy, popularizing microscale experiments, using virtual or low-cost experiments, utilizing new technologies such as micro- and ultrasonic waves, rationally refining experiment devices, recycling lab materials, and sorting or treating laboratory wastes (Bai et al., 2015; Chen et al., 2013; Wang et al., 2017a, b; Xie et al., 2010a, b). Most papers highlight the green improvement of existing chemistry experiments, especially for organic chemistry experiments. These include the substitution reaction of methane and chlorine with a micro-scale device (Yan et al., 2018), the synthesis of ethyl acetate (Cao et al., 2010), the use of a microscale experiment of determining amino acid (Cai et al., 2013), employment of a series of micro-polymer chemistry experiments (Li et al., 2011), selection of a green fiber catalyst used in organic synthesis (Xie et al., 2016), and the choice of a solvent-free emulsion and foam fractionation, respectively, in the extraction of lycopene from tomato sauce (Zhu et al., 2008; Wang et al., 2010a, b).

Furthermore, green chemistry practices have been suggested to nurture students' awareness of environmental protection and other related areas. For instance, Lin et al. (2020) designed a green electrochemical experiment for college students. They found that it increased students' theoretical knowledge with respect to learning and enhancing green chemistry competencies. Zhou et al. (2018) designed a green chemistry experiment using corncobs as raw materials to synthesize biodiesel, ethanol, and sunscreen to reinforce students' awareness of GSC. Another organic experiment used a safe surfactant to teach and increase students' independent thinking and collaborative abilities (Lu et al., 2017). A model based on "asking-thinking-doing" evaluation was proposed for GSC practical work to enhance students' innovative thinking (Wang et al., 2010a, b). All in all, the topics for GSC experiments and their improved methods are very diverse. The experiments

employed are often concerned with fostering students' abilities beyond normal practical skills.

5.3.3. Focus 3: Students' awareness of GSC

Investigations on college students' awareness of GSC are still limited. But the results show that many college students with majors in chemistry or related subjects possess only basic knowledge about green chemistry. They tend to misunderstand the role of green chemistry and its potential role (He et al., 2013; Qiao et al., 2013). This is similar to the results found for secondary education. Zi (2014) implemented a questionnaire to college students. The results indicated that most participants had a sound awareness of environmental protection. However, their associated behaviors were quite feeble due to their weakly-related knowledge of green ideas.

6. Discussion and conclusion

According to a very basic didactic model (Hudson and Meyer, 2011; Sjöström et al., 2020), the four main components of educational practices are the teacher, the student(s), and the content, including their interactions and embeddedness in certain contexts. The relationship can be visualized with the aid of a tetrahedron (Fig. 5).

Context considers classroom-based teaching, educational authorities, society, and culture in the global environment. School and education authorities provide places, standards, and resources for the occurrence of teaching and learning. Society takes over the responsibility for public education and is the original model for schooling (Dewey, 1990). And culture is highlighted here, following the proposed reference subjects of science education by Duit (2007). According to the features and contexts of Chinese GSCE, the framework found in our research is suggested by Fig. 6. This is based on the didactic model given in Fig. 5, the above-mentioned Burmeister et al.'s (2012) model of GSCE, and the identified foci the current study.

GSCE is mainly composed of the GSCE forms found in the classroom plus teaching and learning through practical work, extracurricular activities, and public education in society. The latter comes especially from industry, museums, non-governmental agencies, and social media. These agencies can support GSCE as outreach activities and can influence chemistry teaching as well. International trends in GSCE and the developments of GSC can provide potential contexts and contents for GSCE and influence the attention of educational administration reflecting curriculum standards and textbooks. The local culture, as an invisible assistant can promote the actual implementation of GSCE. All of these together can influence GSCE contents or contexts in connection to another two GSCE core components, namely students and teacher with related implementation and evaluation. Fig. 6 aims at combining all the different present and potential future aspects of GSCE in China that were found and associated by the authors when performing the literature analysis. It provides a suggestion for reflecting relevant factors influencing GSCE in China (maybe even in other countries as well) and the potential role of relevant actors and fields affected by this development to make them foci of future research and development.

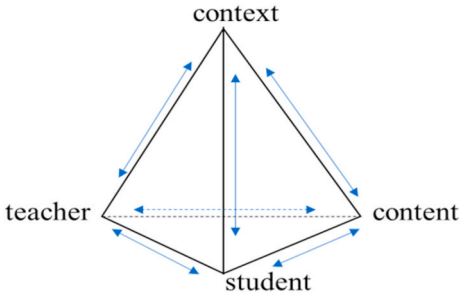

Fig. 5. A didactic model on the interlink of student, teacher, content and context in teaching and learning (adapted from Hudson and Meyer, 2011; Sjöström et al., 2020).

The foci of GSCE in China are broad. The implementation stage of GSCE in Chinese secondary education seems, however, to still be preliminary. It mainly focuses on introducing the first elements of GSC, improving obligatory experiments, and suggesting new teaching strategies. The implementation of GSCE at the secondary level remains mostly at the classroom teaching and practical work level. Aside from this, exercises about GSCE are increasingly emphasized. Connections to other educational stakeholders can only rarely be found. Chinese secondary education seems, however, to be poised on the brink of the next development, including highlighting GSCE in the *high school chemistry curriculum standards (2017 version)* (MOE, 2018). But teaching examples and models, chemistry textbooks based on the local culture, and teacher education about GSCE are all quite limited. Teachers' and students' awareness of green chemistry ideas and the associated behaviors remain weak. This is primarily due to the exam-oriented, textbook-focused teaching found throughout China, even though students' environmental awareness falls in line with their scientific competencies without gender or geographical differences. An international evaluation of students' awareness of GSCE (Ribeiro and Machado, 2013) and the related abilities based on GSCE have not yet been fully utilized or discussed. SSI-related GSCE has initially been discussed, but broad implementation is still lacking. The Chinese cultural and philosophical view of GSCE is rarely discussed in the academic literature. Programs for non-formal and informal education on GSCE as an effective support structure for the formal schooling system is not a major focus in the literature.

Tertiary GSCE in China has been going on for about 20 years. There are plenty of related textbooks which have been published. Green chemistry ideas have slowly infused chemistry education. Chinese green chemistry research has also reached the top of the list in international publications. There are several papers on tertiary GSCE, and teaching strategies and green chemistry experiments have the highest emphasis. Since a broader field of chemistry sub-disciplines exists, there is still a clear lack of consensus whether GSCE should be restricted to a single course or made into a cross-disciplinary endeavor throughout the different fields of teaching tertiary chemistry. Within the general realm of chemistry, there remains a lack of systemic introduction into green chemistry, insufficient teaching practice examples in detail, and a need for new and creative green chemistry experiments for all sub-disciplines. The current study suggests that the main method is still frontally-directed teaching instead of inquiry-based teaching at the university level. There also seems to be only a loose connection between chemistry teaching and chemistry research. This is a not a fully-exploited resource at present. Teaching the use of the latest GSC research outputs at Chinese universities is an approach with a lot of potential (Ma and Zhao, 2018). Due to excellent international research work on GSC research, researchers at Chinese universities should more responsibly disseminate GSC ideas and their research works in GSCE. They should also explore rational and available teaching and learning resources for secondary school teachers by cooperating with schools or building non-formal open laboratories. The development of new and effective pedagogies for GSCE is still necessary, since this is an ongoing challenge for instructors. The core concepts of sustainability are rarely mentioned in many GSCE research works. Newer theories and the *Sustainable Development Goals* (SDGs) are experiencing the same situation. Setting up related websites about GSCE can assist both teachers and students in gaining transferable resources for both secondary and tertiary GSCE (Kennedy and Chapman, 2019). Compared with secondary GSCE, tertiary education is generally more diverse and advanced. It tends to use more modern education technologies and ideas, implement improved experiments geared towards nurturing students' related abilities, and employ examples of various outreach activities. But, the literature also suggests that college students' awareness and understanding of GSC remains low. Among the reasons for this may be the mainstream role of direct teaching, the existing limits in necessary resources, and the

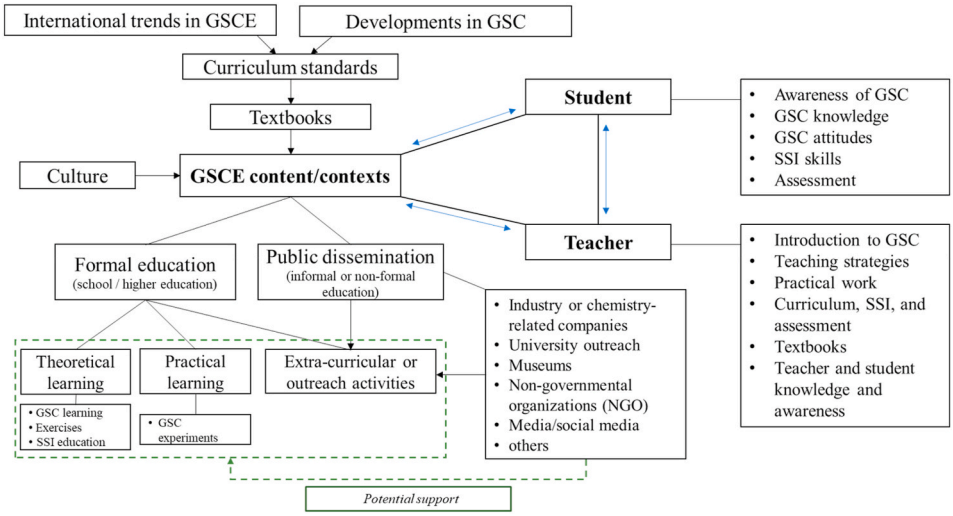

Fig. 6. A suggested framework for reflecting influential factors and potential actors or fields of action to be reflected when it comes to implementing GSCE in China.

current gap between scientific research and GSCE.

Communities of GSCE research in mainland China are not yet visible at the secondary school level. Chemistry education researchers may need more communication about GSCE, not only at the national level, but also internationally. The strengthening of both communication and cooperation between in-service secondary school chemistry teachers and university teachers, other related agencies and authorities remains especially important. The *Green Chemistry Creativity Biannual Competition* for senior secondary students held by the Taiwan education and environmental protection authorities has been successfully launched since 2014 (Green Chemistry Education Website, 2020). It has strongly promoted GSCE. This might be one idea for inspiration, just like the many other related activities in various countries or regions around the world. Many innovative green chemistry experiments are invented each year by Chinese teachers and students. Most of them are introduced in the journal of *Chemistry Education in Taiwan*, but also in other international journals. Related summer camps and workshops for students and teachers have also been supported since 2018 by the Taiwan educational authority. To assess the benefits of international collaboration and communication with western researchers, related research about SSI in Taiwan (Chang and Chiu, 2008; Wang et al., 2017a, b) may be helpful. This could provide mainland China with secondary chemistry education examples which can be used to further strengthen GSCE. Workshops about GSC experiments or online GSCE resources (Kennedy and Chapman, 2019) are another idea which can provide support to teacher educators and secondary school teachers in order to popularize GSCE in secondary education (Kulandaisamy and Karpudewan, 2020).

CRediT authorship contribution statement

Baoyu Li: Conceptualization, Methodology, Software, Visualization, Formal analysis, Writing – original draft, Writing – review & editing. **Ingo Eilks:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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